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ORIGINAL RESEARCH PAPER

TRANSFORMING WINDOWS GLASS WASTE INTO FUNCTIONAL AGGREGATES FOR SUSTAINABLE COMPOSITE PRODUCTION

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Abstract: The use of glass waste in construction materials has gained increasing attention, particularly for window glass from insulating and simple glazing systems. This study investigates the feasibility of using such waste as aggregate in concrete, focusing on its effects on density, consistency, and mechanical properties. Waste glass was used as partial replacement of natural aggregates (up to 10 %), in both fine and coarse fractions. Results indicate a moderate decrease in compressive strength (from 29 - 30 MPa to 26 MPa), while maintaining values above 20 MPa, which are acceptable for structural applications. The particle size plays a key role, with the 0 - 2 mm fraction contributing to improved matrix densification and better performance. Overall, the findings demonstrate that insulating window glass waste can be successfully valorized as a sustainable alternative aggregate in concrete production, with limited impact on mechanical properties.

Keywords: *aggregates, composites, insulation windows glass, simple windows glass*

INTRODUCTION

Due to the environmental impact of waste glass, many studies aim to identify alternative ways to valorize this waste in composite materials [1]. Life Cycle Analysis (LCA) assessments mentioned in the international literature show that replacing natural aggregates with recycled glass reduces the consumption of mineral resources and CO_2 emissions associated with extraction and transport [2, 3]. Also, the recovery of insulating glass contributes to reducing the volume of landfilled waste [4, 5], given that these products have a long lifespan and generate significant amounts of waste during building renovation [6]. The utilization of waste glass as aggregate in construction materials has become a topic of interest in recent years, in the context of circular economy and waste reduction [7, 8]. The glass from insulating glass, after removal of metal and plastic components, can be crushed and used as fine or coarse aggregate in concretes, mortars and asphalt mixtures. Experimental research indicates that partial replacement of natural sand with glass aggregate, in proportions of 10 - 30 %, determines a density comparable to that of the reference sample. A slight increase in the compressive strength at substitutions of up to 20 %, due to the filling effect and the sharp-edged texture, which improve the paste–aggregate interface was reported [9, 10]. However, at higher substitution percentages, mechanical strength may decrease and the risk of alkali-silica reaction becomes relevant, which is why the literature recommends the use of mineral additives, such as ashes, metallurgical furnace slag, marble etc. to reduce alkali-silica reaction and increase durability [11]. Nodehi et al. studied influence of glass waste aggregate in the production of composite materials and role of the shape over properties [12]. The composite material obtained with glass aggregates showed cracks, which was explained by the destructive alkali-silica reactions. Sharma *et al.* showed that replacing more than 50 % of natural coarse aggregate with glass aggregate leads to a reduction in the 28-day compressive strength of concrete, reaching up to 9.09 % [13]. Fernando *et al.* reported the effect of particle size on the properties of mortar composite materials [14]. The compressive strengths of materials containing different percentages and sizes of glass waste decrease for all waste sizes as the degree of replacement increases. Compared to the control mix, the compressive strength decreased by 9 % to 23 % for particle sizes smaller than 4.75 mm (including the 1.18 - 4.75 mm range) as the replacement level increased from 0 % to 100 %. This reduction in strength is mainly attributed to the higher friability of glass, which can lead to premature failure in compression. Limbachiya [15] and Rahim *et al*. [16] reported 23 % and 21 % reductions in compressive strength, respectively, at a 50 % replacement of sand with glass, attributing the loss to poor adhesion caused by the smooth texture of the glass surface, which limits mechanical interlocking and weakens the paste-aggregate interface. An increase in glass waste aggregate content leads to a decline in flexural strength, attributed to the weaker adhesion at the surface of the glass particles. In literature [17] was reported the flexural strength ranges between 3.00 and 5.27 MPa, with a decrease of up to 2 % as the proportion of glass aggregate increases. Similarly, Park *et al.* [18] observed a reduction in flexural strength of up to 3 % for a 15 % glass aggregate addition. Kisacik's research [19] showed that when glass waste was used, the flexural strength decreases by up to 8 %. The possibility to obtain homogeneous mixtures must also be considered, as the shapes of the glass waste can affect uniformity, particularly at higher replacement levels of up to 60 % [17].

Hashim *et al.* [20] studied the influence of ground glass waste on compressive strengths at 28 and 90 days. The compressive strength values were higher than those of the mixture without waste by 26.1 %, 20.7 %, 18.5 % and 10.3 % for 5, 10, 15 and 20 % ground glass waste. This increase can be attributed to the supplementary formation of calcium silicate hydrate (C–S–H) during the pozzolanic transformation, as the resulting C–S–H gel enhances the interfacial transition zone and, consequently, improves the mechanical strength.

The pozzolanic reaction of glass powder is directly influenced by particle size, the reduced particle size leads to an increased pozzolanic reaction. It should be noted that a positive influence is also given by calcium oxide originating from the glass waste, it reacts with water to form $Ca(OH)_2$, which combines with silica causing the generation of a greater amount of C-S-H. Therefore, the compressive strength of composites with glass waste as a cement substitute shows an upward trend [21]. Similar results have been published in the literature [22, 23], the optimal amount of cement substitution with glass powder being determined at 15 % [24].

The mechanical strengths of composites with ground glass waste, after 28 days of hydration have values between 39 - 52 MPa [25]. Liang *et al*. observed that small glass particle sizes led to higher strengths, especially at high aging ages, due to the specific surface area of the particles [26]. After 90 days, the sample with 10 % waste glass (powder) showed a compressive strength of 66.5 MPa with a strength increase of 3.7 % compared to the control sample [27]. The observed results can be explained by the enhanced degree of cement hydration, along with the decrease in the average size of ground glass particles from 33 µm to 22 µm, which contributes to a finer and more homogeneous pore structure [28]. For diameters greater than 33 µm, the samples had a lower compressive strength than the reference sample [9, 24, 29, 30]. Nassar and Soroushian [31] studied the use of different percentages (15, 20 and 23 %) of ground glass waste with an average particle size of 25 µm as a partial replacement for cement. The compressive strength results showed that the materials with 15 and 20 % waste glass had a higher compressive strength compared to those without waste, but increasing above this value did not produce changes in terms of compressive strength [20]. Tuncan *et al*. reported a 6 % increase in tensile strength when adding 15 % of ground glass waste, due to the amorphous structure, as fine as cement, and the appearance of hydration products [32].

Replacing 10 - 20 % of cement with glass powder can reduce CO_2 emissions associated with cement production and improve the durability of the mixture [9]. The use of glass waste in composite materials is a sustainable solution for reducing the environmental impact and for the valorization of recyclable materials [33]. Ground glass can be used both as aggregate and as an addition with a binding role, replacing part of the cement. When used as aggregate, glass particles contribute to improving workability and can increase compressive strength, however, the alkali-aggregate reaction must be controlled by using finely ground glass or pozzolanic additions.

Research shows that an optimized mixture, in which glass is used simultaneously as an aggregate and as a cement substitute, can achieve mechanical performances comparable to conventional materials. Studies also indicate an improvement in resistance to chemical attack and a reduction in permeability. Despite the growing interest in the use of recycled glass in concrete production, most studies have focused on container glass, while the potential of waste glass originating from insulating and simple window glazing systems remains insufficiently explored. Furthermore, limited information is available regarding the influence of different particle-size fractions and the simultaneous replacement of fine and coarse aggregates on concrete performance. Therefore, the objective of this study is to evaluate the feasibility of using insulating window glass waste as a partial aggregate replacement in concrete and to assess its effects on fresh and hardened concrete properties, with particular emphasis on density, consistency, compressive strength, and the role of particle size distribution. Among the various recycling pathways for insulating glass waste, usage as aggregate in concrete has emerged as a potentially sustainable solution. However, additional studies are required to evaluate its impact on concrete performance and to identify suitable replacement rates that ensure both technical and environmental benefits.

MATERIALS AND METHODS

The cement used in the study is a CEM II A-LL 42.5R type cement. This is a composite Portland cement with added limestone. It is a cement that develops a high initial strength from the first days of the mixture formation. Its composition is formed by 80 - 94 % clinker, 6 - 20 % limestone and 0-5% minor constituents. The resistance class 42.5 represents its compressive strength determined at 28 days, in MPa.
In this study two different types of windows glass (WG) waste were used: insulating glass (ST) and simple glass (SS). The wastes were cleaned, crushed and sieved in order to obtain particles with a size similar to that of natural aggregates. The aggregate obtained was characterized by bulk density, specific density, absorbability, grain shape, texture, and was separated by sieving.
The aggregates used to obtain composite materials are granular mineral materials. The aggregates are obtained by washing the raw ballast excavated from the Bistrita river. The presentation of aggregates by grade is shown in Figure 1.

Aggregate 1 (0 - 4 mm)

Aggregate 2 (4 - 6 mm)

Aggregate 3 (8 - 16 mm)

Figure 1. *Image of the aggregates used*

The shape of the granules changes the volume of voids between them. Classification of the main shapes of aggregate particles: rounded, irregular scaly, angular, elongated. The main aspects that are important from the point of view of the shape and texture of the aggregates are: the degree of roundness, sphericity, the proportion of scaly granules, the surface texture. Thus, rounded granules give the mixture easy workability, which requires less mixing water and is easier to compact; elongated granules give the mixture a resistance reduced by 20 - 25 % compared to the mixture made with rounded granules.
The properties of aggregates were determined: density, granulometric distribution, resistance to fragmentation/crushing, impurity content etc.
The grain size was determined for each aggregate grade: Grade 1 (0 - 4 mm), Grade 2 (4 - 6 mm) and Grade 3 (8 - 16 mm), using the dry sieving method. The data obtained, expressed as simple rejection (Rs) and cumulative screening (Cc), are presented in Table 1. The granulometric mixture of aggregates from which the composite material is formed is obtained as a mass percentage of the aggregate passed through sieves with mesh sizes of 0.125 mm; 0.25 mm; 0.5 mm; 1 mm; 2 mm; 4 mm; 8 mm and 16 mm. The percentages of the grades will be chosen in such a way that the granulometric curve of the aggregate mixture falls within the limits of the two maximum and minimum curves.

Table 1. *Granulometric analysis data [%]*

Sieve [mm]	**Aggregate 1**		**Aggregate 2**		**Aggregate 3**	
	Rs	**Cc**	**Rs**	**Cc**	**Rs**	**Cc**
16	-	-	-	100	4	96
8	-	100	1.8	98.2	81.62	14.38
4	4	96	75.4	22.8	13.77	0.61
2	31	65	20.4	2.4	0.42	0.19
1	21	44	2	0.4	-	-
0.5	14.4	29.6	0.4	-	-	-
0.250	16.4	13.2	-	-	-	-
0.125	8.2	5	-	-	-	-
0.063	4	1	-	-	0.19	-
Pan	1	-	-	-	-	-
∑ RI+P	100		100		100	

Table 2 presents the mass percentages of the aggregate mixture for the preparation of composite materials.

Table 2. *Aggregate mixture grain size*

Aggregate	**%**	**0.125**	**0.250**	**0.500**	**1**	**2**	**4**	**8**	**16**
0-4	41 %	2.78	6.90	15.05	22.99	29.04	37.91	41.00	41.00
4-8	22 %	0.00	0.00	0.00	0.15	0.27	0.46	19.26	22.00
8-16	37 %	0.00	0.00	0.00	0.00	0.06	0.10	2.26	35.54
	100	2.78	6.90	15.05	23.14	29.37	38.46	62.52	98.54
	min	1	3	8	12	21	36	60	95
	max	5	8	20	32	42	56	76	100

The composition of C16/20 concrete class was used, in which 2, 4 and 10 wt.% ST was used as replacement for different types of aggregates.

To obtain the composite material mixture, the following steps are considered:

a) Characterization of the raw materials by chemical, physical and mechanical properties;

b) The reference mixture was established based on the performance parameters of the composite material. Thus, we established that a composite material with a compressive strength of 20 MPa, determined on a standardized cube (150x150x150 mm), with a maximum aggregate size of 16 mm and a consistency of S3 is to be obtained.

c) Establishing the water/cement ratio (w/c) from which we calculate the amount of cement required in the reference mixture and the granulometry of the aggregates, based on the reference granulometric curves.

d) Preparing the raw material mixture and obtaining the composite material.

Preparing the raw material mixture consists of dosing them by weighing (on a technical balance with one decimal place) each type of aggregate, cement, additive and measuring the volume of water. The dosage of the components is done in the following order: the aggregates of the 8 - 16 mm grade are introduced, followed by the following grades in the order of the grain size, homogenized for 10 - 15 seconds, after which half of the water and the required cement are added, continuing the homogenization for 10 - 15 seconds. The additive is mixed with the remaining water and added together to the homogenization. A homogenization of 80 - 120 seconds follows, after which the composite is poured into molds.

The homogenization was carried out in a mixer with a capacity of 180 L, with a supply voltage of 230 V, power of 1000 W and a working speed of 26.6 revolutions per minute. In the reference mixture, in order to obtain the composites with waste in the basic matrix, 2 %, 4 % and 10 % (relative to the total mass) of crushed insulating glass waste, with particle sizes ranging from 2 mm to 6 cm, were introduced. Subsequently, for the comparative evaluation of the influence of the type of waste, the impact of introducing simple glass, with different particle sizes, in proportion of 4 % wt., was analyzed, in order to determine the effects on the physical and mechanical properties. The compositions of the composite materials with glass waste are presented in Table 3.

Table 3. *Composite materials with glass waste [kg]*

Material type	Cement	Additive	Glass (SS)	Insulating windows glass, ST	Sort 1	Sort 2	Sort 3	Water	a/c
MC_Ref	302	1.67	-	0	729	365	729	185	0.61
MC_2ST	302	1.67	-	46.24	729	365	729	185	0.61
MC_4ST	302	1.67	-	92.5	729	365	729	185	0.61
MC_ 10ST	302	1.67	-	23.1	729	365	729	185	0.61
MC_ref1	302	1.67	0	-	729	365	729	185	0.61
MC_2SS1	302	1.67	92.5	-	729	365	729	185	0.61
MC_2SS2	302	1.67	92.5	-	729	365	729	185	0.61

The following characteristics of the resulting concrete were noted: density, fresh and hardened, the consistency of the fresh concrete mix, the compressive strength, etc. A C16/20 concrete was used as a comparative mixture. All tests were conducted in accordance with the Romanian standard, in a certified concrete station laboratory.
To determine the density, standardized containers (150x150x150) mm are used, which are initially weighed and after being filled with material (the compaction is carried out according to standards). For the density of the hardened composite material, the weight of one cubic meter of material after hardening is determined.
The compaction method consists of measuring the compaction of the material in its fresh state, under its own weight, using a truncated cone into which the composite material is inserted. A ruler is placed on the truncated cone and the compaction (h) in mm is measured, the value according to which its consistency is measured.
Each result presented was obtained from the average of three readings.
Raw materials were characterized by: X-ray diffraction was performed with PANalytical X'PERT PRO MRD X-ray Diffractometer (PANalytical XRD, Malvern, UK); Fourier transform IR spectroscopy (FT-IR) was performed with a Thermo scientific "NICOLET" 6700 TF-IR spectrophotometer (Thermo Fisher Scientific, Waltham, MA, US). For the determination of the elemental analysis, a QUANTA 3D SERIE AL99/D8229 electron microscope was used (Quanta 3D–AL99/D8229–FEI Company, Hillsboro, OR, US).

RESULTS AND DISCUSSION

Characterization of glass waste used as aggregate replacement

The experimental research aimed to use glass waste from the insulating glass industry in the structure of a composite material with an average strength class of 20 MPa. The waste was used as an aggregate substitute, the degree of replacement being 2 %, 4 % and 10 % by mass. These percentages were selected based on our own experience and data from the literature, in order to obtain a composite with the specified strength class.
The presentation of glass waste from the insulating glass manufacturing industry is shown in Figure 3.

Figure 3. *Windows glass (a) and (b) simple glass (SS), (c) and (d) ST 0 – 2 mm, respectively ST 4 - 6 mm*

The XRD analysis of glass waste from insulating glass aims to identify the crystalline phases present. From a structural point of view, the analyzed waste is an amorphous material, based on a disordered network of silicon dioxide modified by alkali and alkaline earth oxides, such as Na_2O and CaO. From Figure 4 it can be seen that the diffractogram does not show peaks characteristic of crystalline materials, but a structure specific to soda-lime glass, found in amorphous materials.

The diffraction pattern confirms that the silica in the glass waste is in a vitrified state and not in the form of quartz. The low intensity peaks can be attributed to impurities or contaminants, such as quartz particles from dust or sand, calcite resulting from auxiliary materials or traces of metal oxides from the frame. These phases are not characteristic of the glass itself, but appear as a result of the processes of use, dismantling and crushing/grinding of the insulating glass.

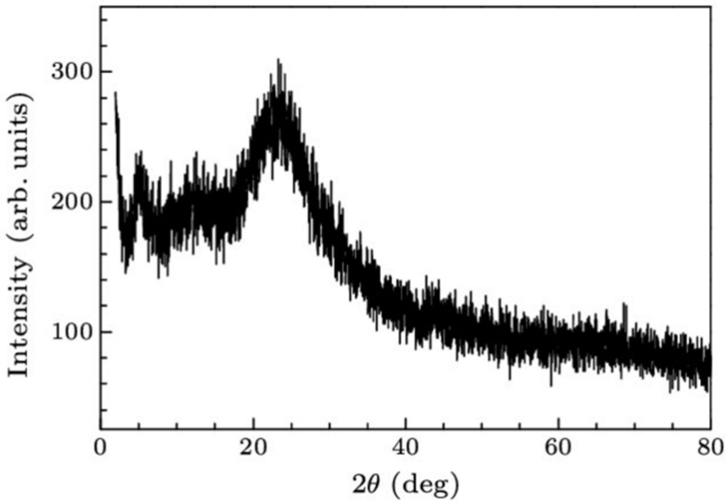

Figure 4. *XRD analysis of insulating glass waste*

The elemental composition of the insulating glass waste is shown in Figure 5.

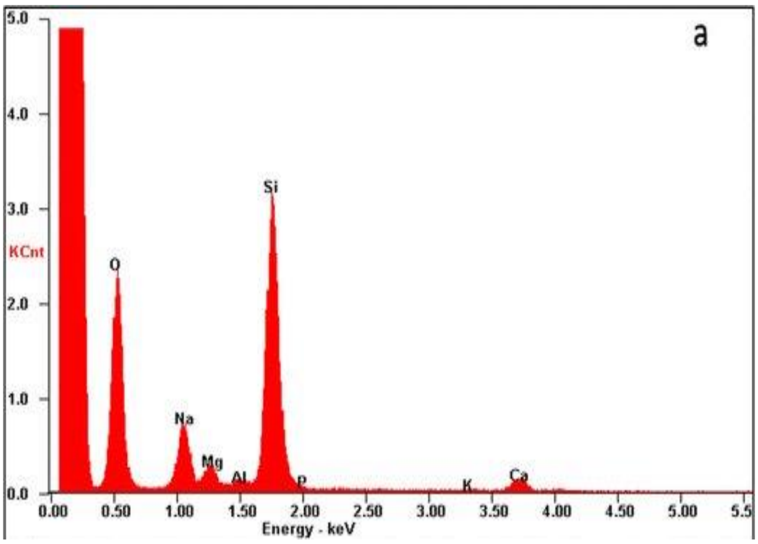

Figure 5. *EDAX analysis of insulating glass waste*

The glass used in windows is, in the vast majority of cases, soda-lime glass. It is chosen because it is transparent, resistant, cheap and easy to produce on an industrial scale. Basically, it is an amorphous material (without crystalline structure) obtained by melting several inorganic oxides. The composition of the glass from insulating glass waste is presented in Table 4.

Table 4. *Oxide composition of glass waste*

Chemical composition	[%]
(SiO_2)	70–75
(Na_2O)	12–15
(CaO)	10–12
(MgO)	1–4
(Al_2O_3)	1–3

The results obtained indicate that the studied waste has potential for use as an aggregate in composite materials.

Characterization of composites with waste glass as aggregate

The behavior of the mixture in which the glass waste (aggregates) is embedded was assessed based on its properties in the wet state: density, settlement, external appearance of the mixture, consistency and workability. For the hardened mixture, the density and compressive strength are studied, its appearance and behavior in an aggressive environment - durability.

The properties were studied in comparison with a standardized mixture that does not contain additives, studying the following influences: the amount of waste incorporated, 2 - 10 % glass wastes as an aggregate replacement; the type of waste used; the influence of the waste dimensions, for a content of 4 % SS, grade 1 0 - 2 mm, respectively grade 2 having diameters of 4 - 6 mm were used.

Density of composite materials

The density of composite materials containing glass waste used as aggregate depends, in addition to the percentage of replacement, on the size of the glass particles and their distribution in the material matrix. In general, the incorporation of glass waste leads to changes in the density of the composites, as glass particles influence the degree of compaction and may result in a more porous internal structure. Particle size distribution also plays a significant role in density: finer particles can integrate more effectively into the matrix, whereas coarser particles tend to cause more pronounced density variations due to reduced compaction efficiency and the formation of voids within the material.

Influence of waste type

Figure 6 shows the density of composite materials with 4 % SS and ST, compared to the reference material.

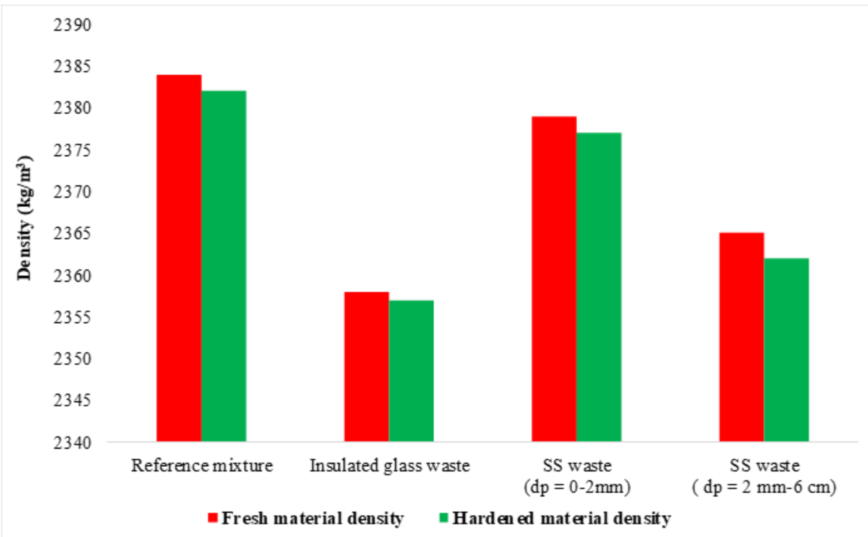

Figure 6. *Density of composites function of type glass aggregate*

The influence of the type of aggregate on the density of the material in the fresh and hardened state was studied for the reference mixture and for composites containing an addition of 4 % waste. It is observed that the reference mixture presents high density values, both in the fresh state and after hardening, which indicates a compact structure. In the case of using glass waste from insulating glass (ST), the density of the material decreases compared to the reference mixture. This decrease can be explained by the differences in density and by the way of integration of glass particles in the composite matrix, which can lead to a less compact internal structure.

For composites with SS with a particle size of 0 - 2 mm, the density values are very close to those of the reference mixture, which suggests a good integration of fine particles in the material structure. In contrast, the use of simple glass with particle sizes between 4 mm and 6 cm causes a reduction in density. This behavior can be associated with more difficult compaction and the appearance of voids in the material structure. In all cases analyzed, the density of the hardened material is lower than that of the fresh material.

Influence of the amount of waste incorporated

Figure 7 shows the density of the material with the addition of ST in different percentages.

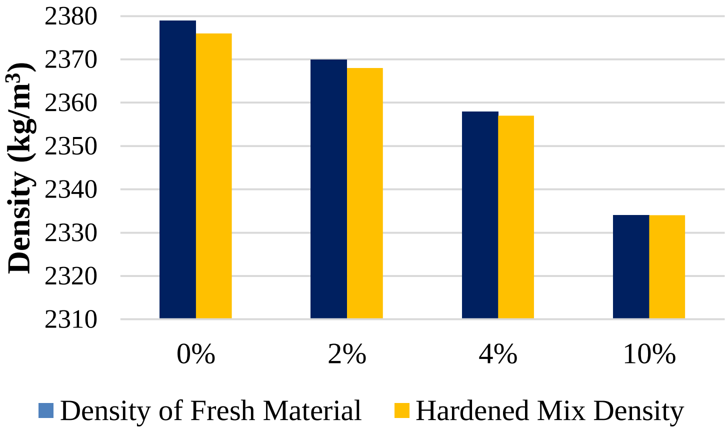

Figure 7. *Influence of waste glass (ST) aggregate content*

Figure 7 shows the density in the fresh and hardened materials depending on the quantities of ST, with the content increase from 0 % to 10 %, the density of the material decreased with 2.1 %. For the reference sample, the density of the fresh material is the highest, and after hardening a slight reduction in the value is recorded, a normal phenomenon due to the hydration processes and water evaporation. As the percentage of glass increases to 2 % and 4 %, the density decreases slightly for both the fresh and hardened material. This trend can be attributed to the lower density of glass particles compared to conventional mineral aggregates, as well as to changes in the internal structure of the mixture. At a 10 % addition level, the lowest density value is observed, with only negligible differences between the fresh and hardened states. Overall, the results indicate that the incorporation of ST results in a smaller reduction in composite density, without significant variation between the fresh and hardened material.

Influence of granulometry

Figure 8 illustrates the density of the reference composite and of the mixtures containing two types of glass waste, showing that density decreases with increasing waste particle size.

It is observed that the reference mixture presents the highest density values, both in the fresh state and after hardening, which indicates a compact structure. The introduction of SS with a particle size of 0 - 2 mm leads to a slight decrease in density, but the values remain close to those of the reference mixture. This variation suggests that the SS aggregates integrate well into the material matrix, without modifying the compactness of the mixture.

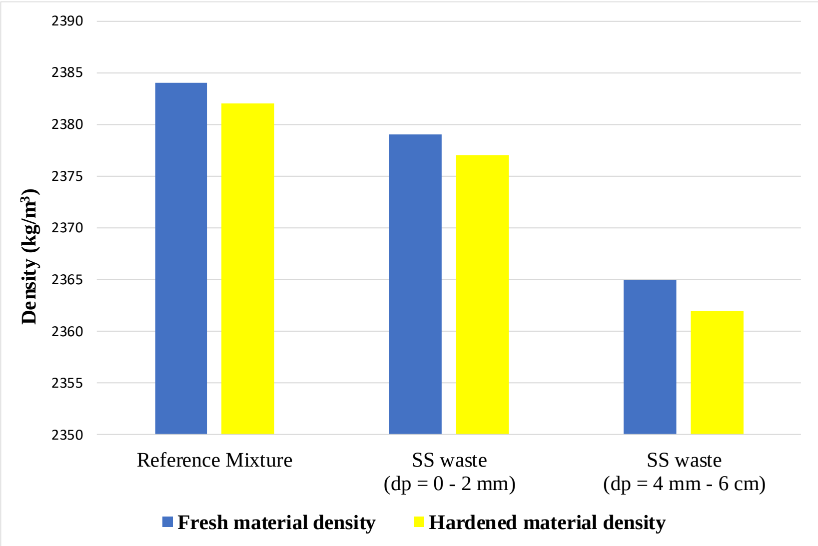

Figure 8. *Influence of simple glass granulometry on density at 4 % SS*

On the other hand, in the case of using SS of 4 mm - 6 cm, a decrease in density of up to 1 % is observed. The decrease can be explained by the fact that larger particles generate a less compact internal structure. The results indicate that the size of the aggregates influences the density of the composite, with finer particles having a lower impact. Using glass waste as aggregate is an efficient recycling solution, without producing density changes greater than 1.4 %.

Consistency and workability

The workability of a composite material is an important aspect for its use. Its homogenization, compaction and final characteristics as a finished material are influenced by the workability. As can be seen in Figure 9, the workability of the composite material falls into a settlement class S3, the height range between 100 - 150 mm.

Figure 9. *Measurement of settlement during experiments*

With respect to the influence of aggregate type on composite consistency, the reference material presented a slump of 110 mm, whereas the mixtures incorporating SS or ST aggregates recorded a slump of 100 mm, suggesting that the type of aggregate does not significantly influence consistency. Figure 10 shows the influence of the ST content on the consistency of the composite material.

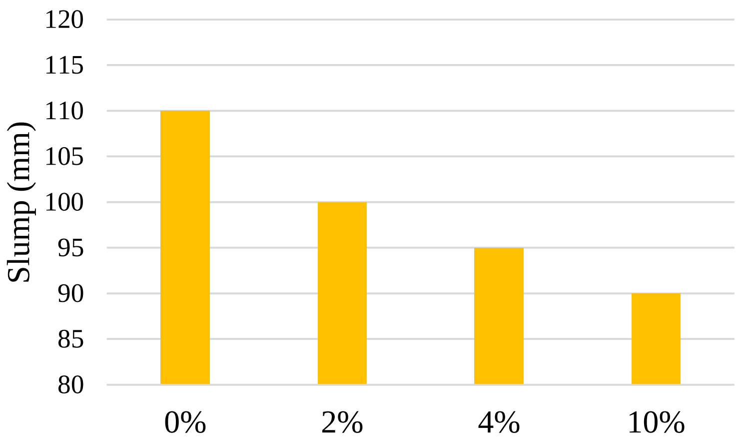

Figure 10. *Consistency of composite material depending on the degree of replacement*

It is found that in the absence of glass addition (0 %), the settlement has the highest value (110 mm). By introducing a percentage of 2 % ST, the settlement decreases to 100 mm. The decreasing trend continues, for additions of 4 %, the settlement decreases by 5 %, being minimal (90 mm) for a content of 10 % ST. The results indicate that increasing the amount of ST determines the decrease in settlement, a reduction in workability or a stiffening of the mixture.

Figure 11 shows the workability for composites with 4 % SS, compared to the reference mix. It was observed that the reference mixture exhibits a slump of approximately 100 mm.

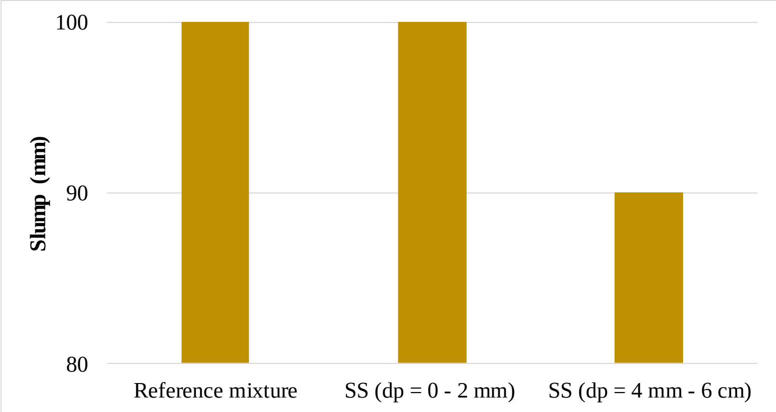

Figure 11. *Influence of aggregate granulometry on consistency, 4 % SS*

The incorporation of SS with a particle size of 0 - 2 mm does not affect this value, indicating that such an addition has no significant influence on the workability of the mixture. In contrast, the use of SS with a particle size of 4 mm - 6 mm results in a decrease in slump of approximately 10 %. Therefore, larger aggregate sizes reduce the workability of the mixture, leading to a stiffer consistency compared to the reference mixture.

Compressive strength of glass aggregate composites

Compressive strength is determined for monoaxial, biaxial and triaxial compressive stresses, performed on cubic, cylindrical and/or prismatic specimens, at different ages (2, 7, 14 or 28 days), under standard conditions, cast and compacted under conditions similar to the placement in the work. Compressive strength is determined using hydraulic presses. Thus, it is determined by applying a uniformly increasing force to cubic specimens. The breaking strength fc (MPa), determined on such specimens is the ratio between the axial compressive force P (N), which causes the fracture, and the surface area of the specimen, Figure 12.

After 28 days, the composite was tested and the compressive strengths were compared with those of the reference sample, corresponding to class C16/20. The research aimed to establish the influence of the type of glass used as aggregate, its content and granulometry.

Figure 12. *Compression test of cubic specimens and their failure mode*

Influence of the type of glass used as aggregate

Figure 13 presents the data obtained for the influence of the type of aggregate. The reference mixture (MC_Ref) records the highest value of compressive strength, 30 MPa. In the case of the mixture containing insulating glass aggregate (MC_2ST), the strength decreases to 29 MPa, a more pronounced reduction being obtained for the mixture containing SS aggregate. The results indicate that replacing conventional aggregates with window glass waste leads to a decrease in compressive strength of up to 10 %, with a less pronounced effect observed for insulating glass and a more significant reduction in the case of single glass. Nevertheless, despite this decrease, all measured values remain above the reference class requirements, with the lowest compressive strength recorded at 27 MPa, exceeding the recommended value of 20 MPa.

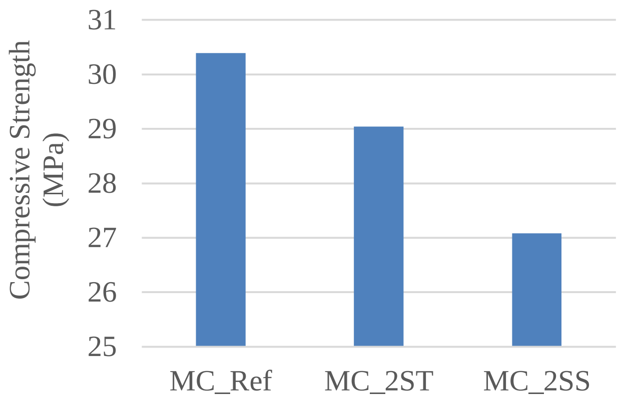

Figure 13. *Influence of waste type*

Influence of aggregate content

Figure 14 shows the compressive strength as a function of the percentage of aggregate.

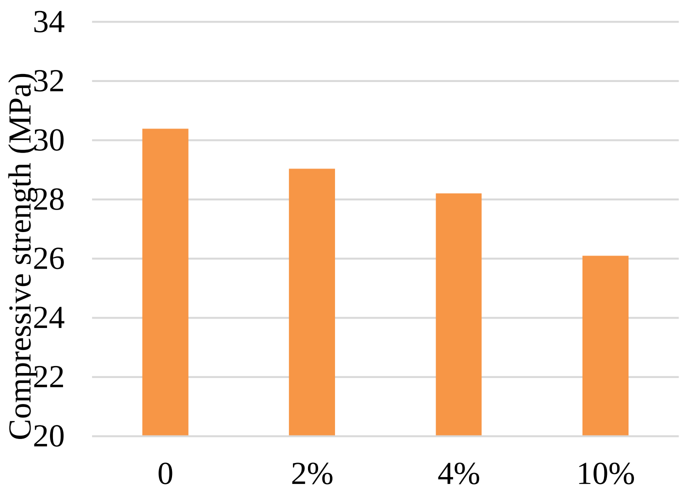

Figure 14. *Influence of the percentage of ST over compressive strength*

It is observed that the mixture without glass aggregate has a compressive strength of 30 MPa. With the introduction of an addition of 2 % ST, the strength decreases to 29 MPa, and increasing the degree of substitution causes a decrease to 26 MPa for a degree of substitution of 10 %. The results demonstrate that increasing the percentage of ST in the composition leads to a decrease in compressive strength; however, as the values remain above 20 MPa, they confirm the potential for valorizing the studied waste glass as an aggregate in composite materials.

The effect of particle size

Figure 15 shows the compressive strength function of the granulometry of the SS.

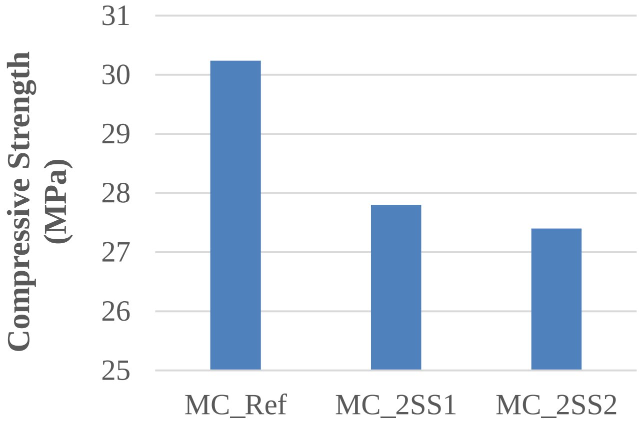

Figure 15. *Influence of aggregate particle size*

From the graph it can be seen that the strength decreases by introducing SS aggregates, but the SS granulometry does not influence the compressive strength.

CONCLUSIONS

The mixtures containing windows waste glass exhibited lower homogeneity, characterized by surface irregularities. Additionally, the fresh density of the resulting materials decreased with increasing waste content, due to the lower density of the waste compared to that of natural coarse aggregates. The mean bulk densities were in the range 2334 - 2379, kg·m^{-3}, lower than the witness sample and were caused by the increase in pore distribution and lower waste density. The highest compressive strength was recorded for the reference sample, whereas the lowest values were observed in the samples with 10 % waste content. The results indicate that the addition of waste negatively affects the properties of concrete, but the percentage decreased in strength was maximum 14 % for concrete with 10 % WG, and 7 % for concrete with 4 % WG. The findings indicate that, compared to the reference sample with a compressive strength of 30 MPa, the incorporation of 2 % ST slightly reduces the strength to 29 MPa, while a higher substitution level of 10 % further decreases it to 26 MPa; nevertheless, despite this gradual reduction with increasing ST content, the compressive strength remains above 20 MPa, supporting the feasibility of using insulating glass waste as a partial aggregate replacement. The experiment revealed that the presence of WG aggregates decreased the compressive strength, but the resulting values were in limits requirement by Romanian standards.

This study demonstrates that WG aggregates (from insulating or single-pane windows) can serve as a viable substitute for natural aggregates. The reductions in mechanical properties were not significant for the investigated replacement levels. Moreover, the valorization of window glass waste as a partial aggregate replacement offers notable economic and environmental benefits. However, further research is required before the widespread implementation of this approach in concrete applications.

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